How to use lidar to study indirect aerosol effects.

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Key questions

- How do changes in aerosol distribution affect cloud properties?

- How is the aerosol distribution changed by human activities?

Key questions

- **How do changes in aerosol distribution affect cloud properties?**
  - **Which aerosol parameters affect cloud properties?**
  - **Which other parameters are important?**
  - **Where do aerosols affect clouds?**
  - **Which cloud parameters are affected?**
- **How is the aerosol distribution changed by human activities?**
  - **Which aerosol parameters are changed?**
  - **Where do relevant changes occur?**
- **How can lidar contribute to answer these questions?**

The bottomline question

Which aerosol parameters affect cloud properties?
Number density of CCN's active at small supersaturation.

Which other parameters are important?
Water vapour density, temperature.

Where do aerosols affect clouds?
Mainly in regions where clouds are forming.

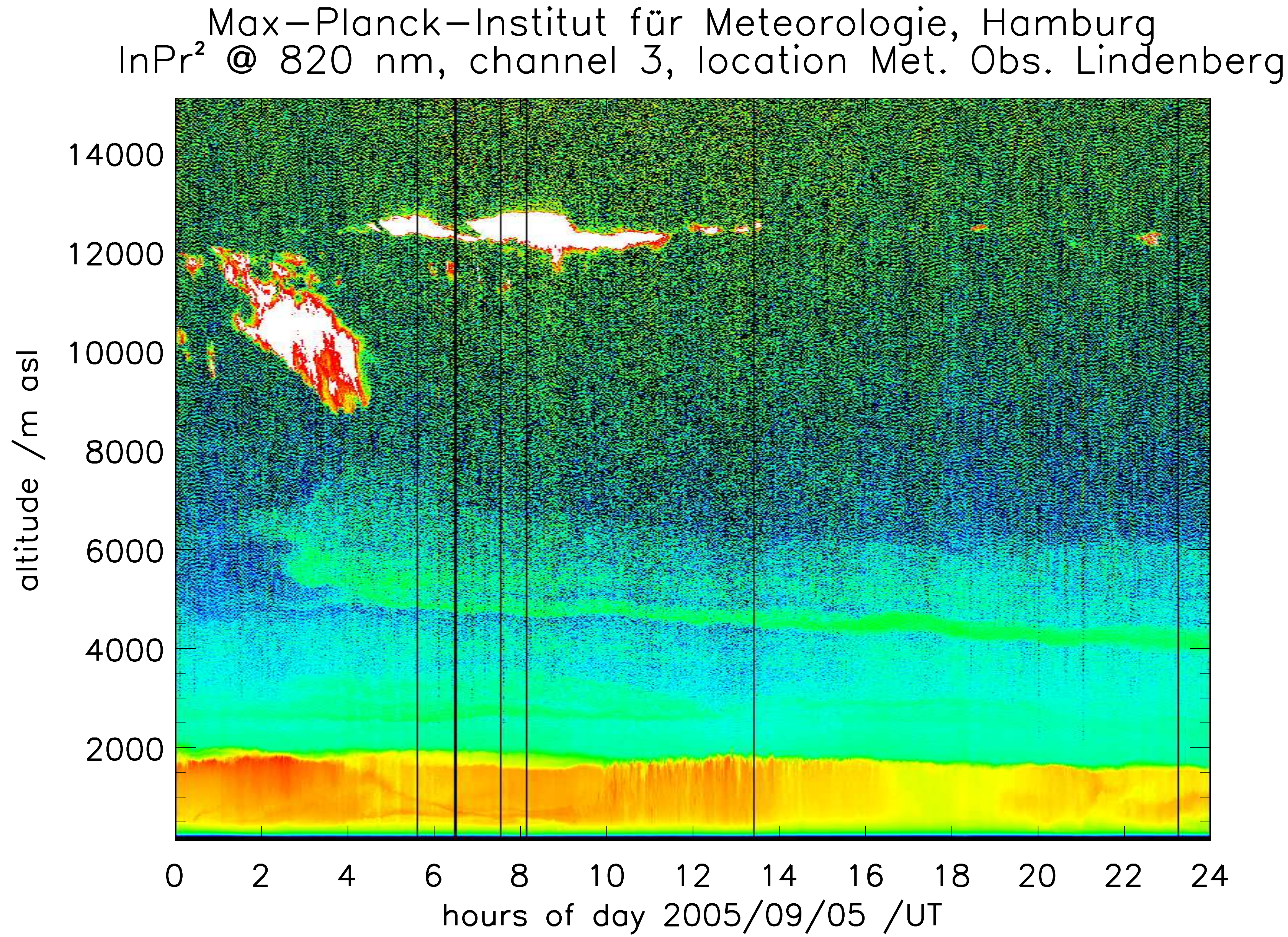
Which cloud parameters are affected?
Directly: Droplet size distribution. Indirectly: Probably all.

How to measure CCN number density, water vapour, temperature, (and resulting cloud droplet size distribution) in cloud forming regions?

Tasks

How to use lidar for measuring CCN number density, water vapour, temperature, and resulting cloud droplet size distribution in cloud forming regions?

1. **Identify cloud-forming regions**
   (a) **convection**
   (b) **large scale convergence**
   (c) **radiation cooling**
2. **Retrieve aerosol size distribution and composition.**
3. **Measure water vapour.**
4. **Measure temperature profile or vertical wind.**
5. **Retrieve cloud droplet size distribution: mainly radar.**



Max−Planck−Institut für Meteorologie, Hamburg
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altitude /m asl
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12000
10000
8000
6000
4000
2000
0
2
4
6
8
10
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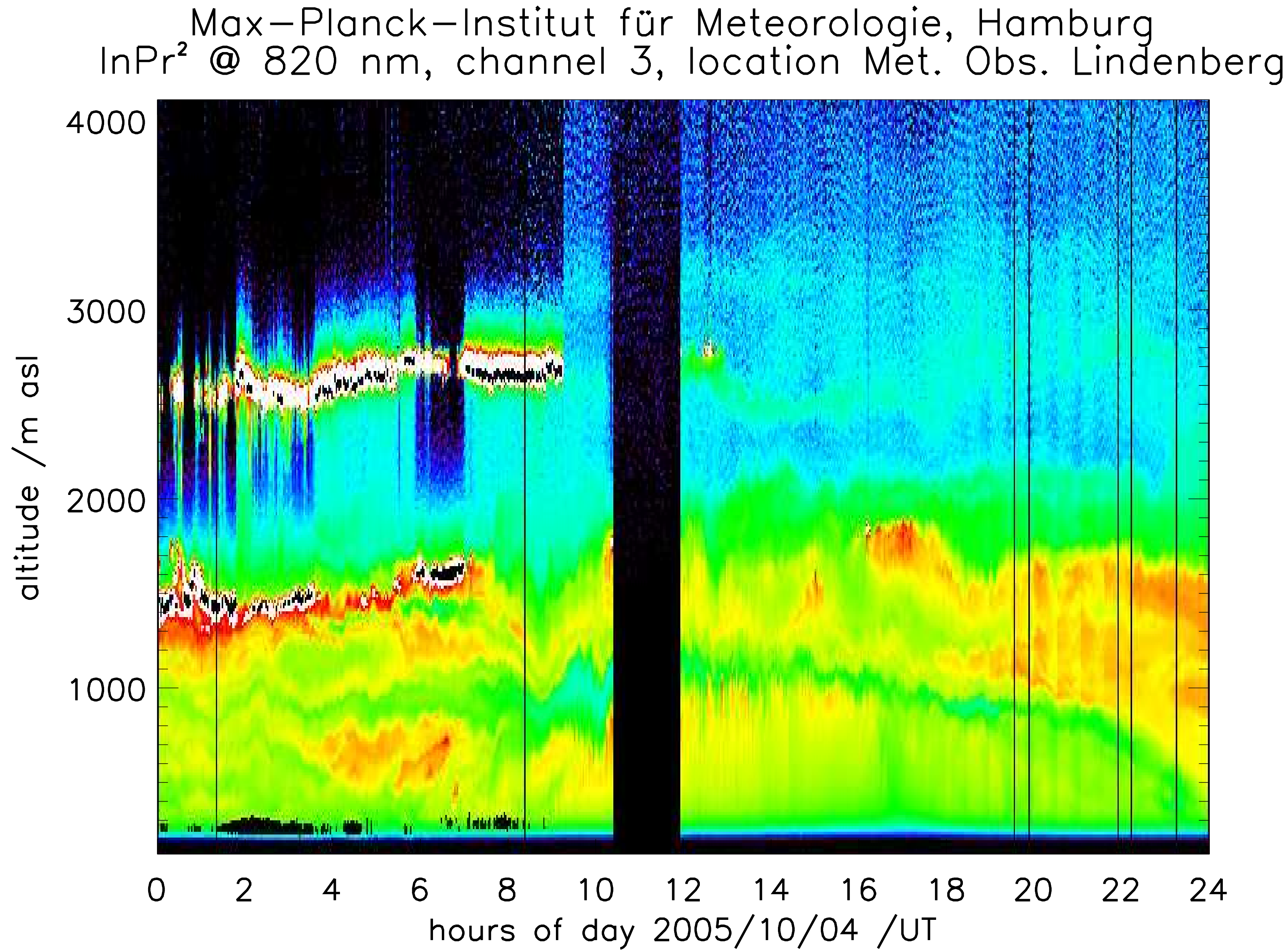
16
18
20
22
24
hours of day 2005/09/05 /UT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lnPr² @ 820 nm, channel 3, location Met. Obs. Lindenberg
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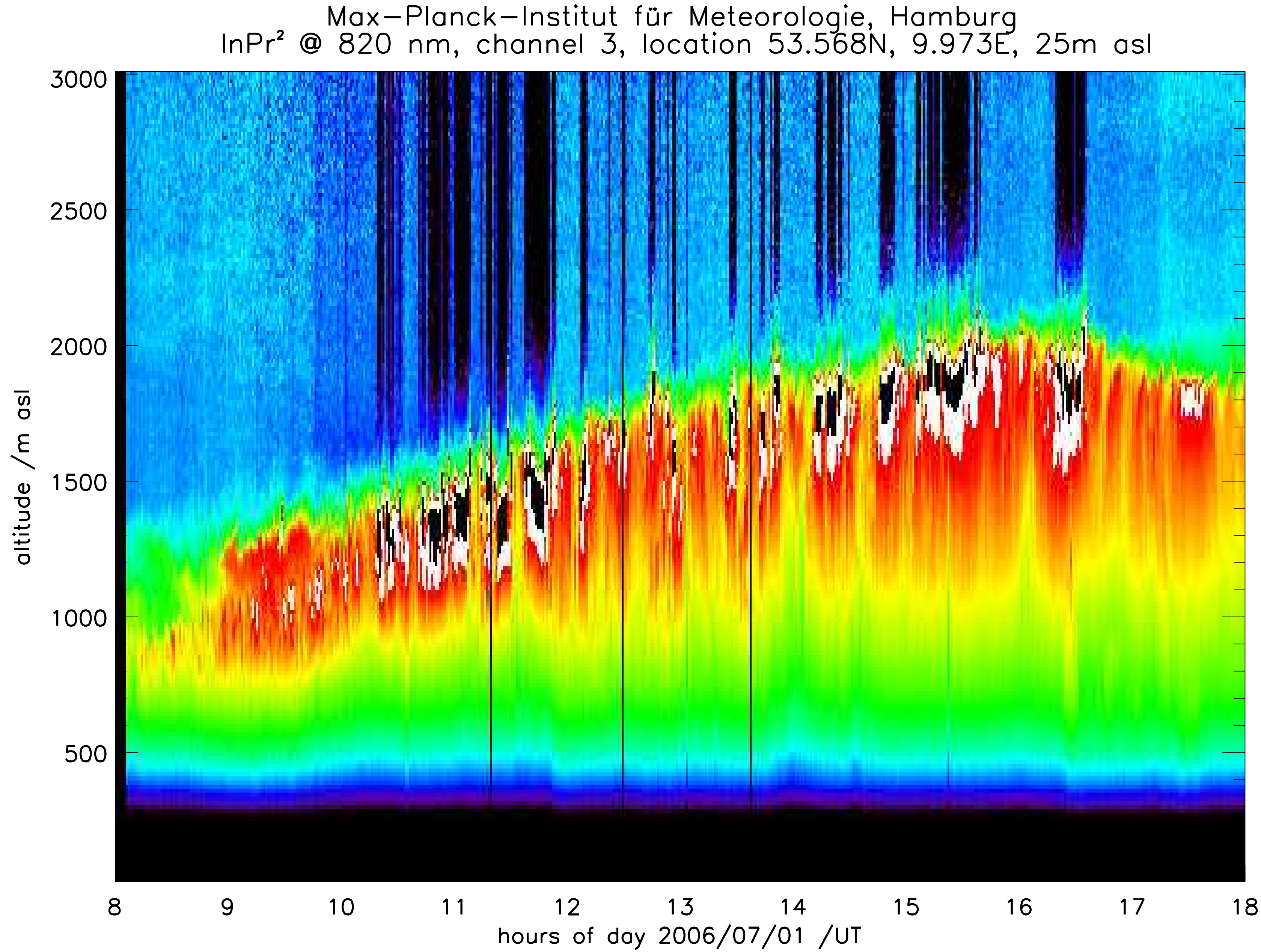
hours of day 2005/10/04 /UT



Max−Planck−Institut für Meteorologie, Hamburg
lnPr² @ 820 nm, channel 3, location 53.568N, 9.973E, 25m asl
altitude /m asl
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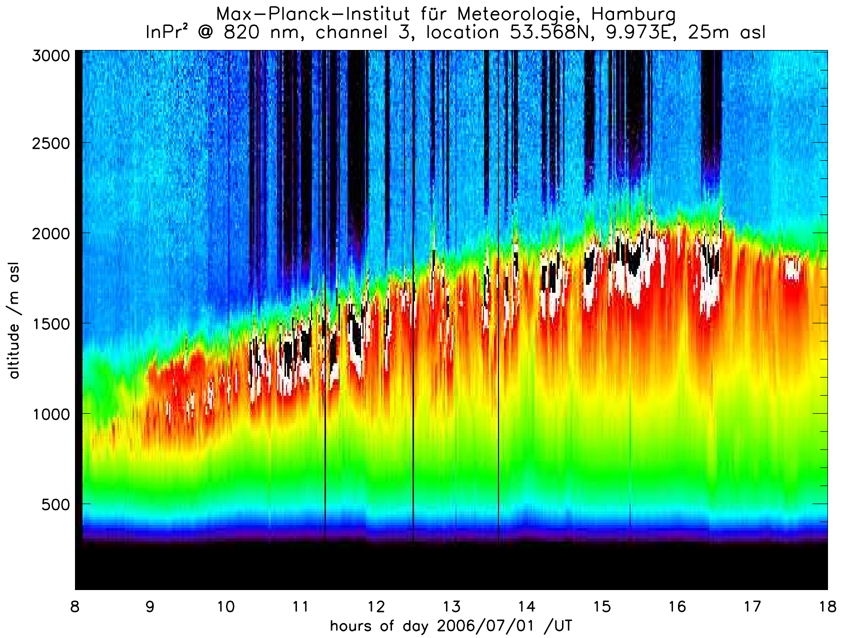
hours of day 2006/07/01 /UT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altitude /m asl
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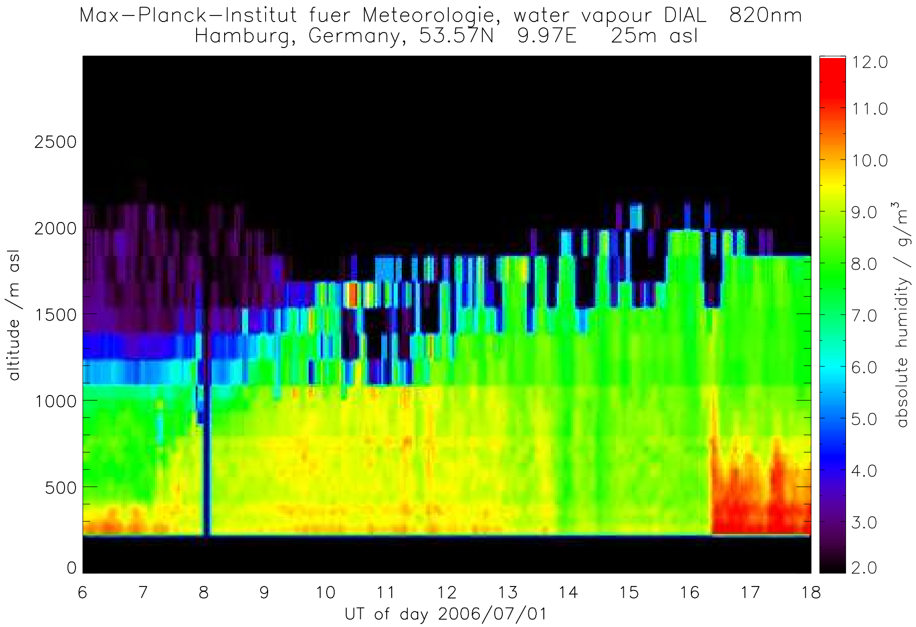
Max−Planck−Institut fuer Meteorologie, water vapour DIAL 820nm
Hamburg, Germany, 53.57N 9.97E 25m asl
altitude /m asl
2500
2000
1500
1000
500
0
6
7
8
9
10
11
12
13
14
15
16
17
18
UT of day 2006/07/01
absolute humidity / g/m³
12.0
11.0
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9.0
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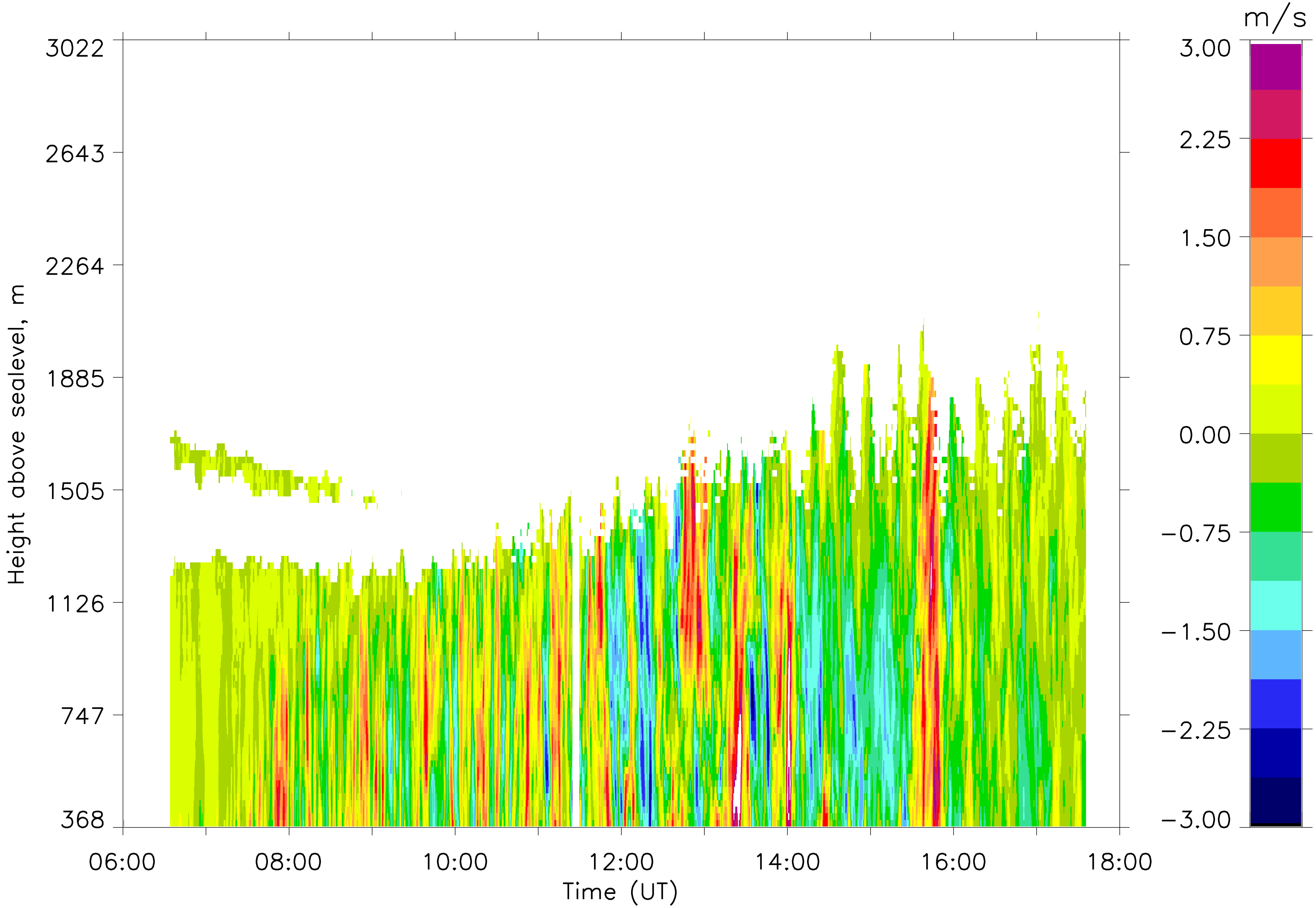
6.0
5.0
4.0
3.0
2.0



m/s
3.00
2.25
1.50
0.75
0.00
−0.75
−1.50
−2.25
−3.00
Height above sealevel, m
3022
2643
2264
1885
1505
1126
747
368
06:00
08:00
10:00
12:00
14:00
16:00
18:00
Time (UT)

Convective cloud formation

- Upward looking backscatter lidar to detect cloud base.
- DIAL to get water vapour inflow and to estimate humidity growth factor.
- Doppler lidar to detect and quantify convective activity.
- Downward looking lidars see only cloud tops and aerosol in downdraft regions.
- CCN?

Large scale convergence

- **Typically slow, non-localized process.**
- **Small vertical velocity (cm/s).**
- **Observations at fixed station not adequate.**
- **Statistical approach feasible, continuous observation required.**
- **Large scale observations required: aircraft, satellite.**
- **Combination with model results/other data.**

Methods

Quantitative retrieval of aerosol parameters from lidar measurements.

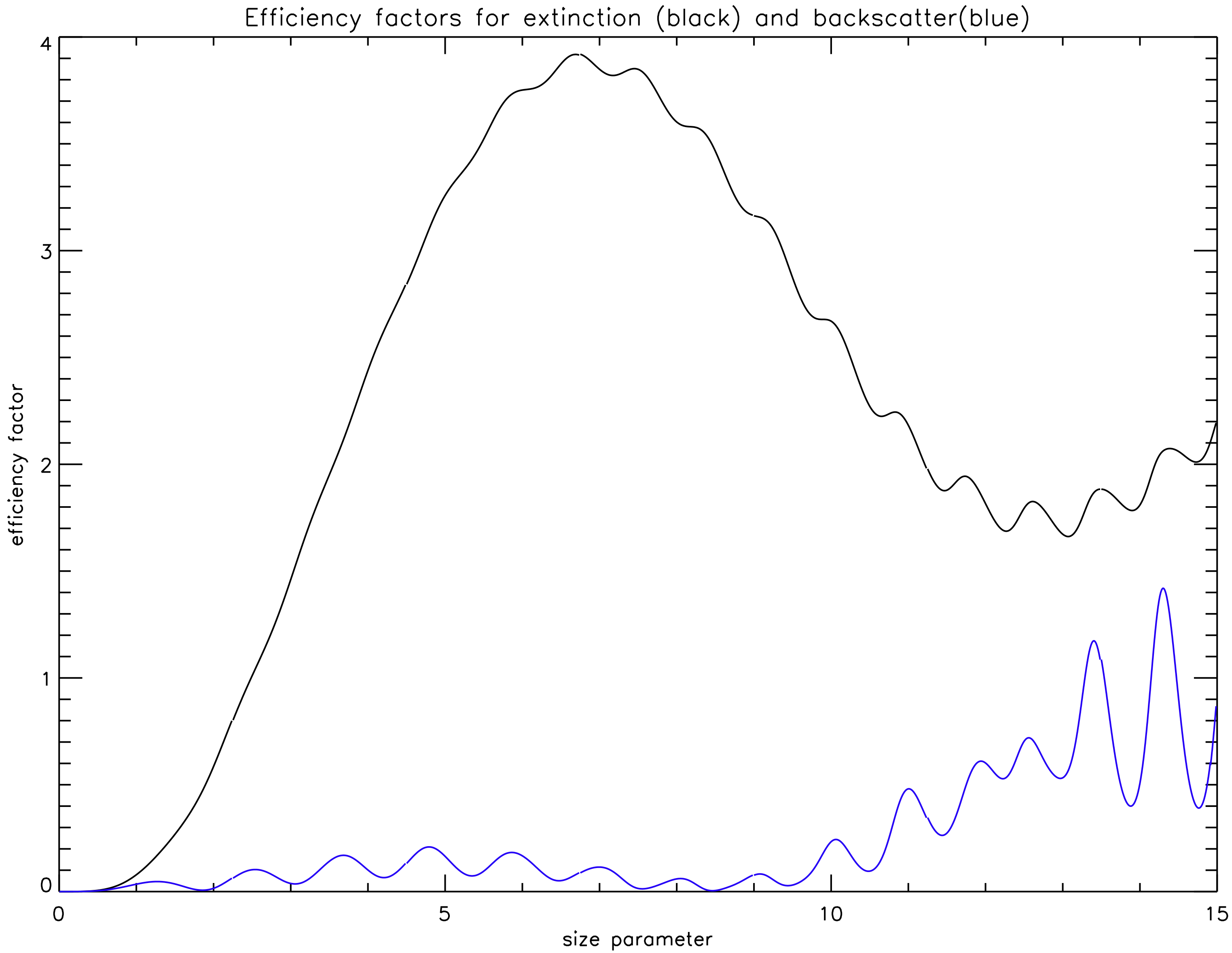
Lidar equation: $P \cdot R^2 = c(\beta_p + \beta_m)e^{-2\int_0^R(\alpha_p+\alpha_m)dr}$

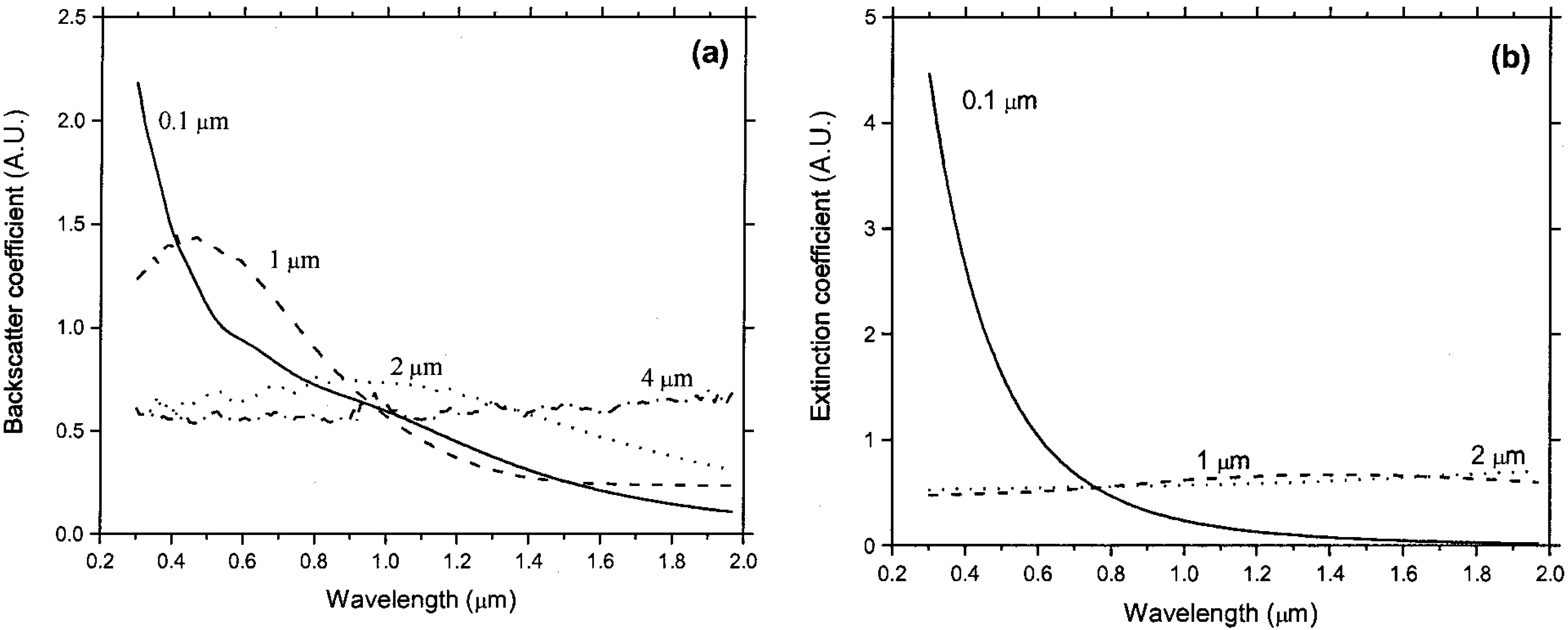
Backscatter lidar: $\frac{d}{dR} ln(P \cdot R^2) = \frac{d}{dR} ln\, \beta - 2\alpha$ **Is NOT quantitative!**

Raman lidar: $\frac{d}{dR} ln(P \cdot R^2) = \frac{d}{dR} ln\, \beta_R - 2\alpha$ **Now widely used!**

HSR lidar: $\frac{d}{dR} ln(P \cdot R^2) = \frac{d}{dR} ln\, \beta_m - 2\alpha$ **Technically demanding!**

Polarisation allows to distinguish spherical from nonspherical particles!


Efficiency factors for extinction (black) and backscatter(blue)
efficiency factor
size parameter
0
1
2
3
4
0
5
10
15



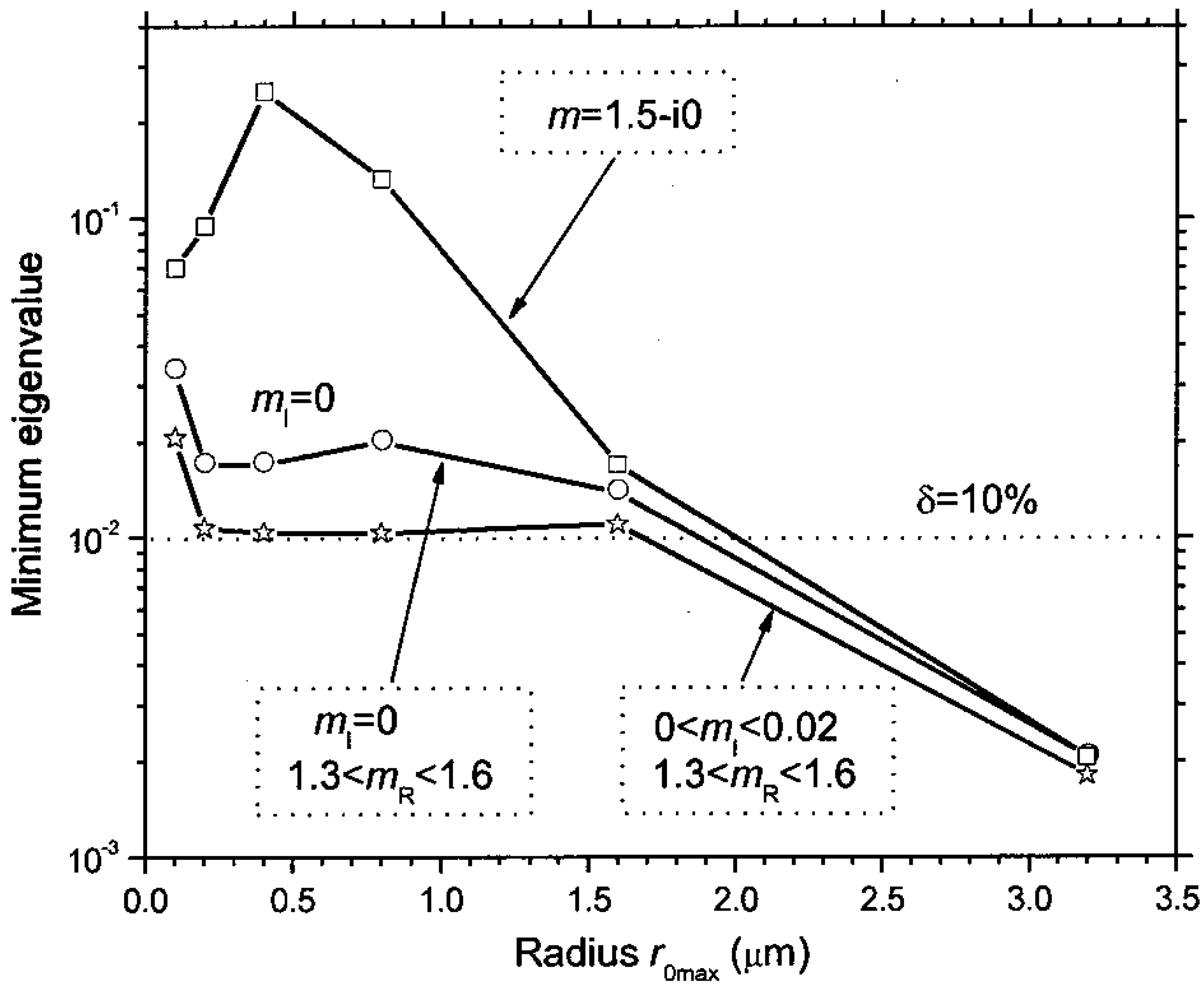
after Veselovskii et al., 2005

Eigenvalue analysis

The measurements of backscatter and extinction at various wavelength are not completely independend. Following Veselovskii et al., Appl. Optics 44, 2005. the degree of linear independence is determined by an Eigenvalue analysis of the covariance matrix

$$C^{\beta} = \| \int_{\lambda_{min}}^{\lambda^{max}} \beta_i(\lambda)\beta_j(\lambda)d\lambda + \int_{\lambda_{min}}^{\lambda^{max}} \alpha_i(\lambda)\alpha_j(\lambda)d\lambda \|$$

where the β and α are the backscatter and extinction coefficients as functions of the aerosol parameters mean radius, distribution width, and refractive index.



after Veselovskii et al., 2005

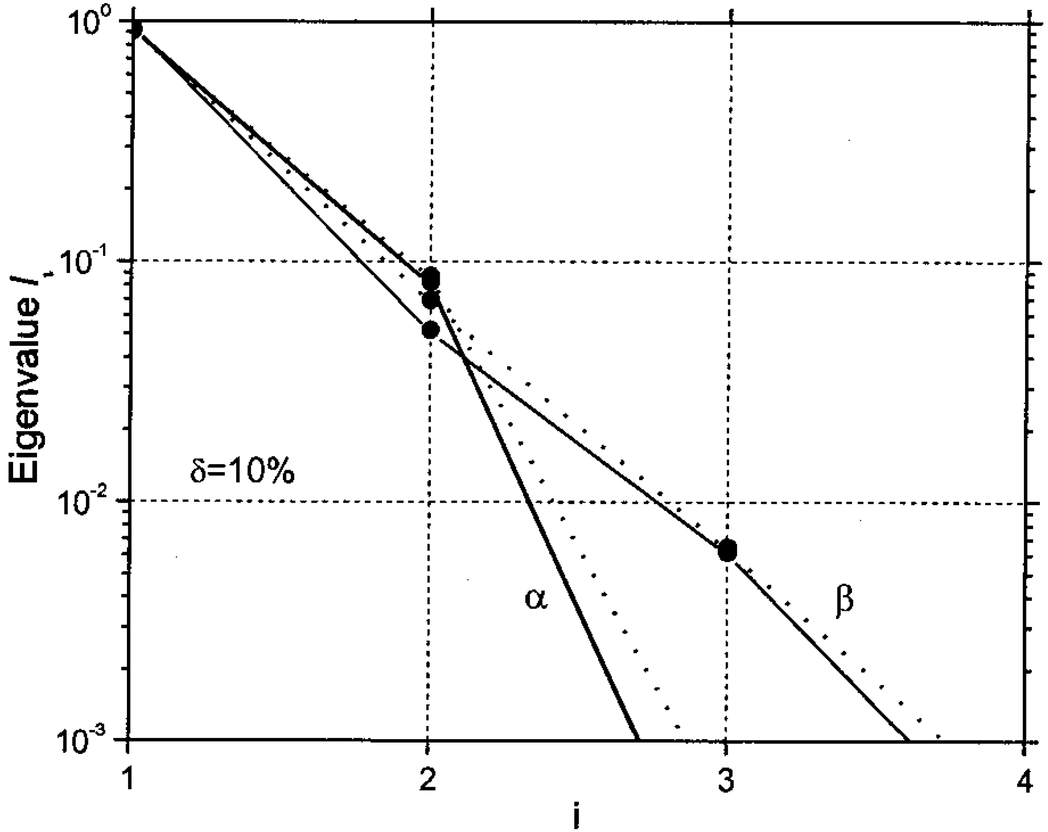


Fig. 14. First four eigenvalues of the covariance matrix calculated for backscatter and extinction coefficients: solid lines, refractive index kept fixed at $m = 1.45 - i0$; dotted lines, case in which m_R and m_I are varied within the range of 1.3–1.6 and 0–0.02, respectively.

after Veselovskii et al., 2005

Summary of Eigenvalue analysis

Main results of the Eigenvalue analysis:

- **Measurements of backscatter and extinction are needed, with errors less than 10%.**
- **3+2: Wavelengths of 355nm, 532nm,and 1064nm (backscatter only) are adequate.**
- **Additional wavelength improve accuracy, but not the range of the retrieval.**
- **Number density, effective radius and complex refractive index can be retrieved.**
- **Constraints on one parameter improve the retrieval of others.**
- **Absorption reduces accuracy of retrieval. Impossible for $m_i > 0.02i$.**
- **For the given wavelength retrieval is restricted to $0.15\mu m < r_{eff} < 1.5\mu m$.**
- **Retrieval errors are less than 50% for r_{eff}, 0.05 for m_r, and 0.005*i* for m_i.**

Number density of CCN may be retrieved if one component in accumulation mode dominates, absorption is small, and the composition is characterized by the refractive index.

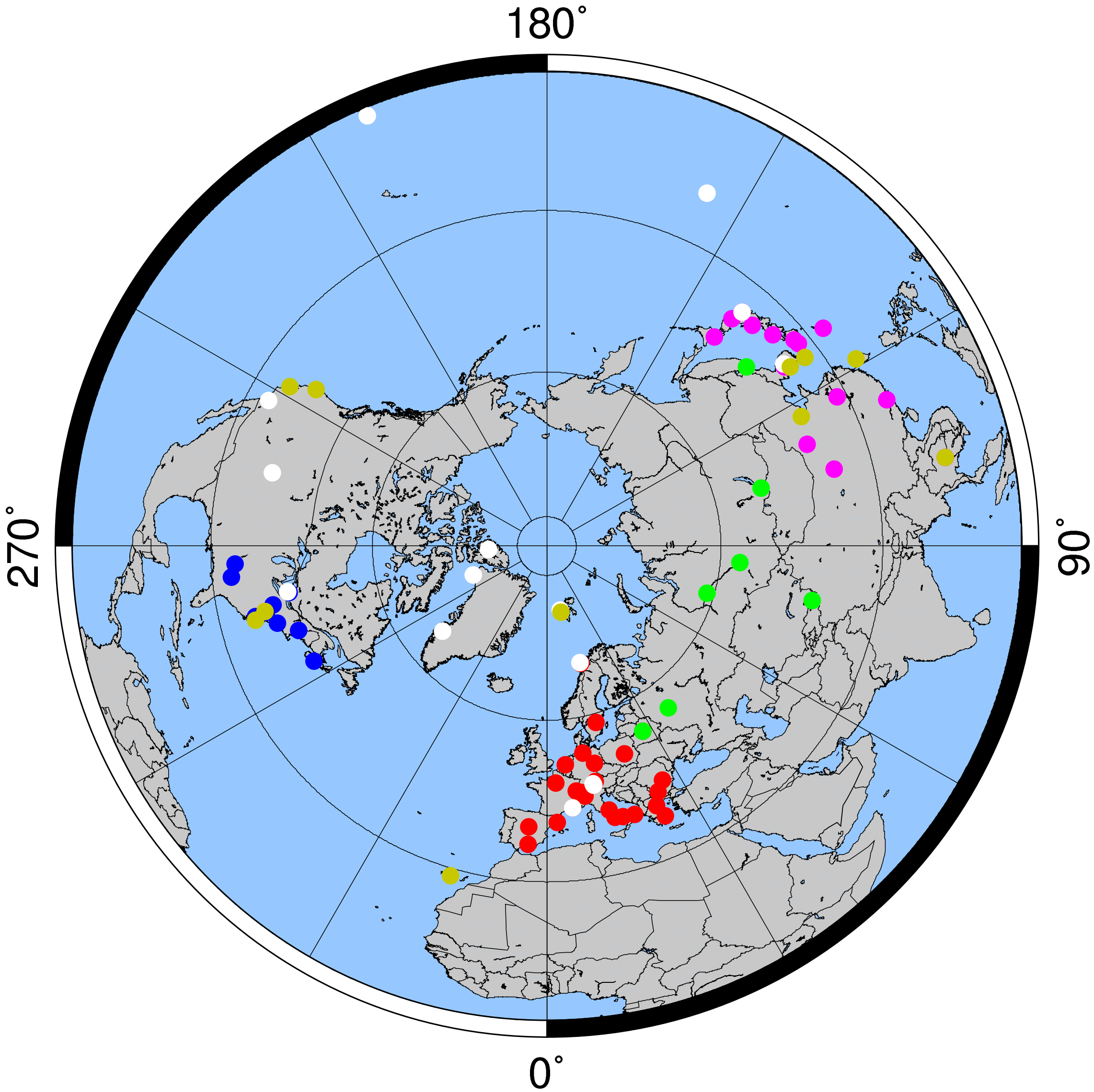
Key question 2

How is the aerosol distribution changed by human activities?

What can be monitored globally with lidar?

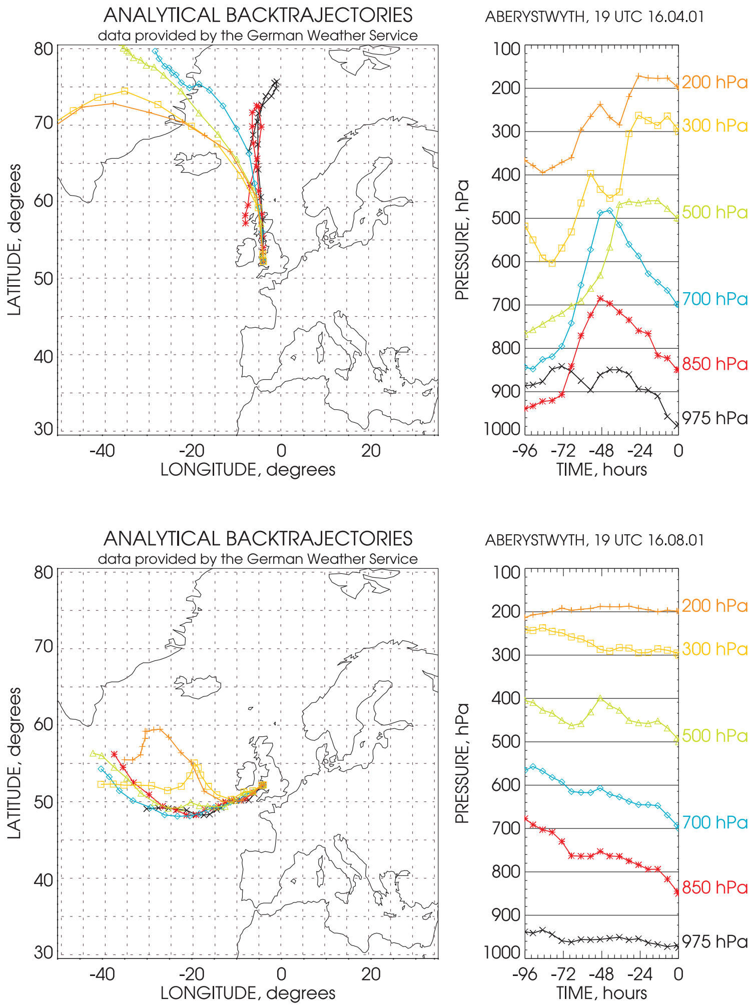
- **CCN concentration: Presently not feasible.**
- **Number density in accumulation mode: Not yet operational, but few suitable stations exist.**
- **Extinction coefficient: About operational at several stations; Space-borne HSRL feasible.**
- **Attenuated backscatter: Many stations, space-borne lidar demonstrated. Useful in combination with other measurements and advanced models;**
- **Aerosol optical depth (sun-photometer): No vertical information to identify the source. Useful in combination with other measurements and advanced models.**

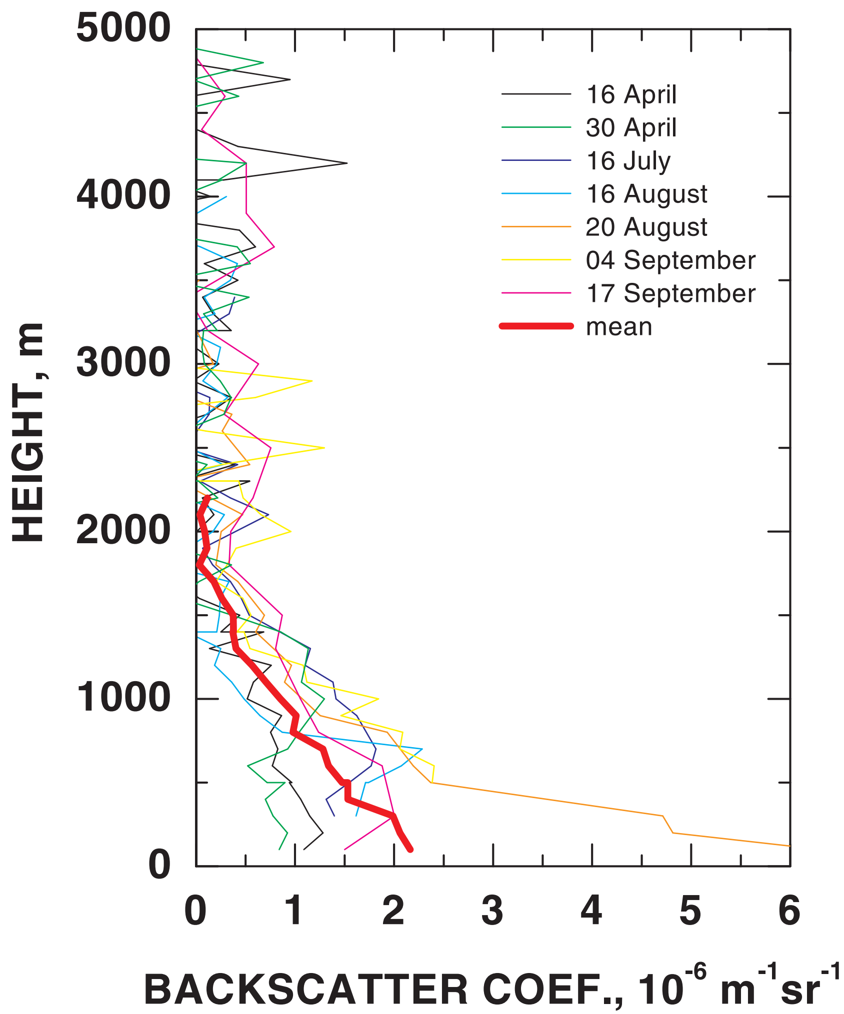
The GAW Aerosol Lidar Observation Network, GALION, is initiated to coordinate aerosol lidar monitoring globally.



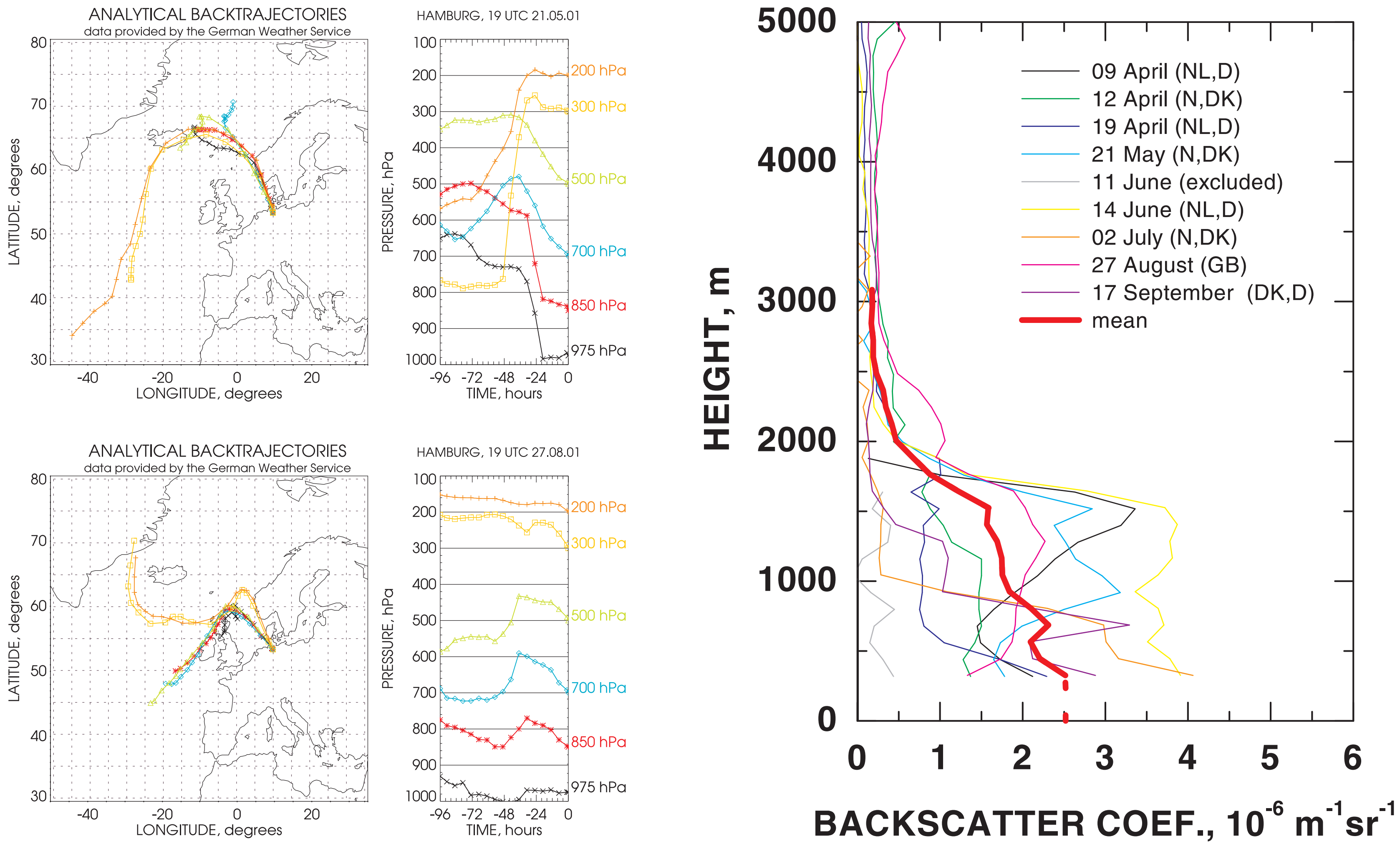
180°
270°
90°
0°

0°
90°
180°
270°





From U. Wandinger et al., J. Geophys. Res. 109, 2004



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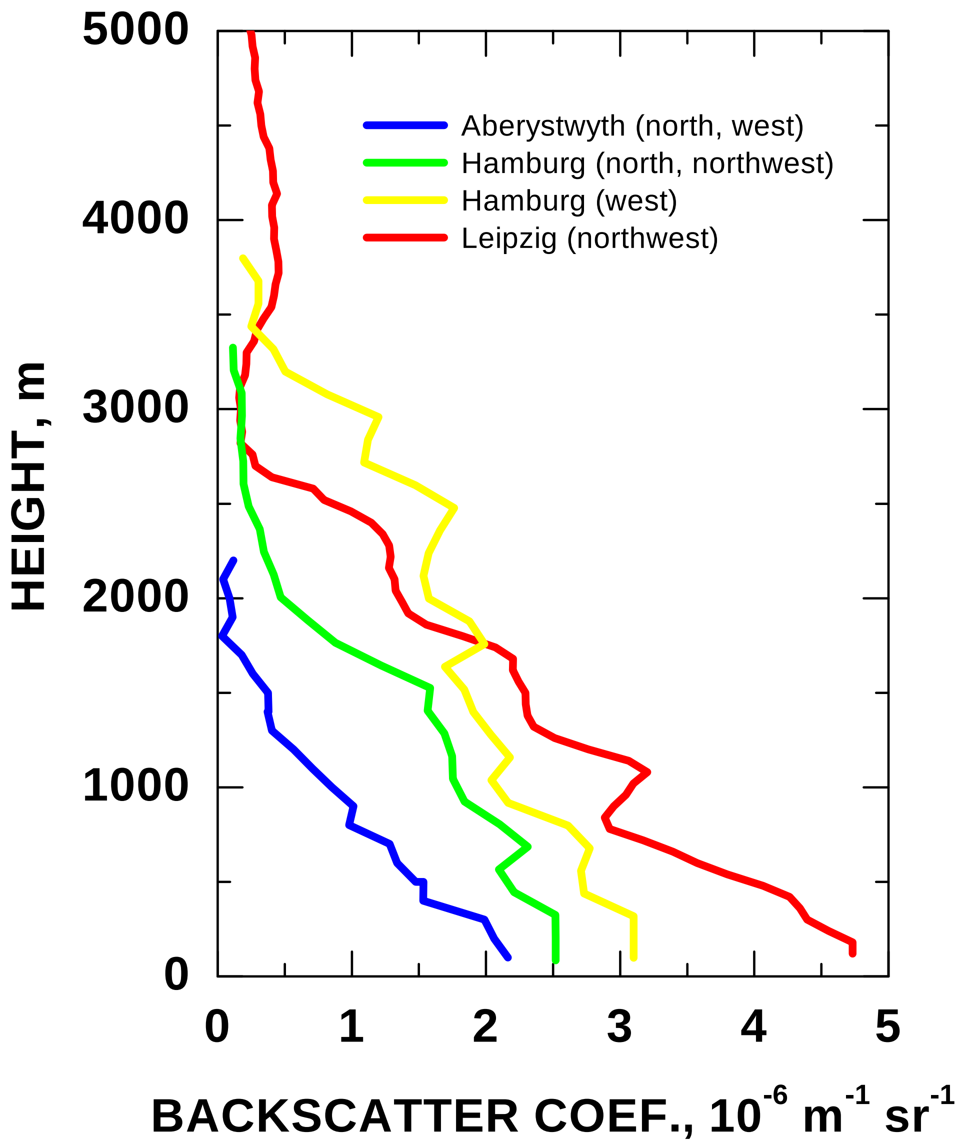

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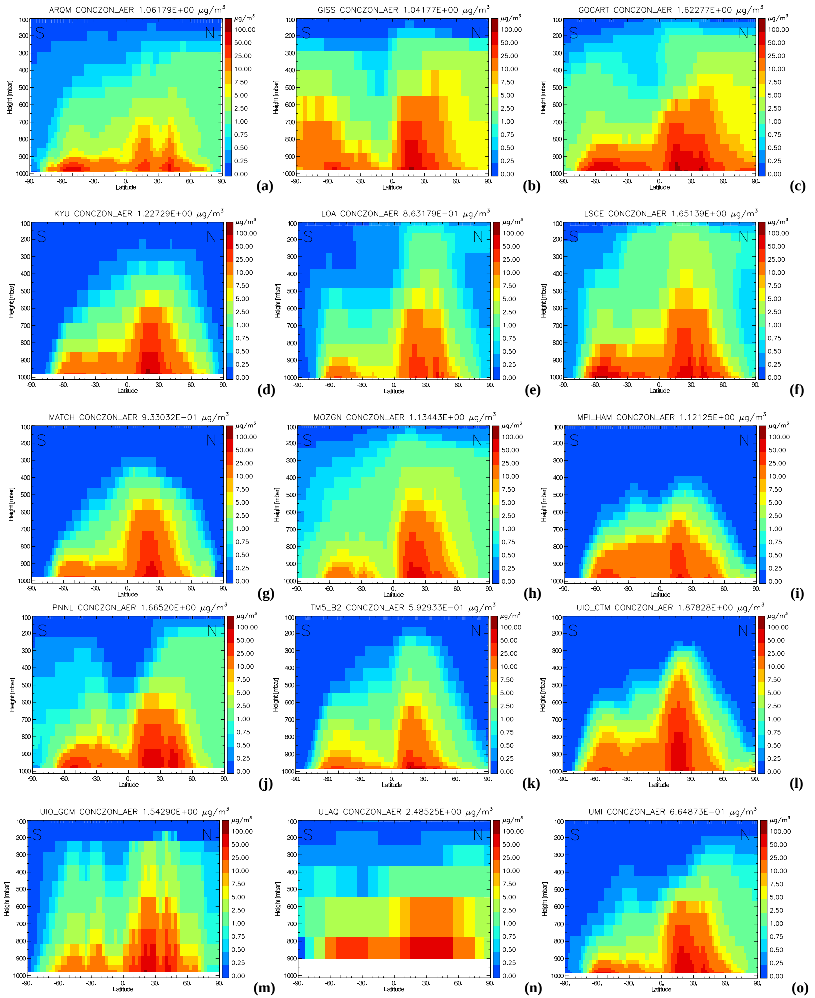

Fig. 10. Zonally and annually averaged concentration of total aerosol in [μg/m^3] (DLR is not shown because of its disregard of the coarse fractions of SS and DU.) Please note, we use a non-linear color scale. The white shading of lowest layer above ground in some models indicates that no data have been available in this layer.

GALION vs. CALIPSO

Why not leave aerosol profiling to spaceborne lidar?

GALION advantages:

- **temporal coverage and resolution (e.g., diurnal cycle!)**
- **advanced observation methods: multiple wavelengths, Raman**
- **can support satellite lidar evaluation by providing**
  - **extinction/backscatter ratio**
  - **Ångström coefficients**
- **observations below clouds**
- **calibration capabilities**
- **long term stability**
- **reference between different satellite systems**

GALION and spaceborne lidars are complementing, not excluding!

Conclusions

- Lidar can make significant contributions to process studies by
  - identifying cloud forming regions,
  - measuring the available water vapour,
  - determining the humidity growth factor,
  - estimating the CCN concentration.
- Lidar can help to assess changes in aerosol distribution by using
  - quantitative methods for ground-based monitoring networks,
  - space-borne lidar assisted by ground-based data,
  - advanced stations for long-term reference.
- In any case vertical information is needed to identify aerosol sources, transport mechanisms, and modification processes.